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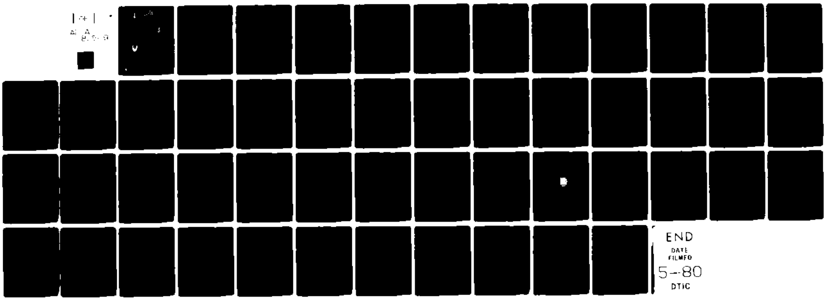

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TECHNICAL REPORT RE-CR-80-1

ACTIVE/PASSIVE LONG WAVELENGTH INFRARED (LWIR) LASER GUIDANCE

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For

Advanced Sensors Directorate
Technology Laboratories

31 July 1979

U.S. ARMY MISSILE COMMAND
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A technical assessment has been made of the opportunities for the use of two or more wavelengths, or of passive and active optical systems, acting in combination for the purpose of missile guidance and target acquisition. In addition, considerations relative to the choice of waveband and current state-of-the-art in components and signal processing are related to requirements for guidance systems. Adverse environments and fire-and-forget capability are emphasized. (cont.)

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20. Most dual wavelength systems described in the literature are of little value for the missile guidance and target acquisition problem where the target is likely to be imbedded in strong clutter. The combination of and active and passive system does offer a unique combination of advantages in contrast to other combinations of active-active and passive-passive systems. The characteristics of an active-passive system operating in the 8-14 μm wavelength region are discussed. The desirability of this wavelength region and the favorable status of component technology for the wavelength region make this an attractive alternative for seekers or trackers for missile guidance. The study also shows the strong need for more data on active signatures for both targets and clutter.

SUMMARY

This study provides a technical assessment of the possible uses of two-frequency, or dual wavelength, systems for applications in missile guidance and target detection. For tactical systems operating at ranges of 5 km or less at ground level the 8-14 μm atmospheric window is the preferred wavelength region offering the additional advantage of a well-developed laser and detector technology.

The combination of a passive 8-14 μm system with an active radar operating near 70 GHz or 90 GHz appears to have potential for military systems, while the combination of an active and passive system operating in the 8-14 μm region offers a unique set of advantages. The information obtained from an active channel can provide for enhanced discrimination of the target when embedded in background clutter facilitating automated systems and providing convenient rejection of fires, flares, and decoys. The vulnerability of active systems in the far IR is considered and it is concluded that detection and countermeasures will not be a limitation. The problem of range closure for an active-passive system is examined with a discussion of anticipated problems and system alternatives. Limitations in modeling systems of interest to this study due to a lack of suitable data are mentioned in several sections.

CONTENTS

ILLUSTRATIONS

TABLES

I. INTRODUCTION

A. Objective of the Study

The objective of the study reported here was a technical assessment of the opportunities for the use of two or more wavelengths, or of passive and active optical systems, acting in combination for the purpose of missile guidance and target acquisition. In addition, considerations relative to the choice of waveband and current state-of-the-art in components and signal processing were to be related to requirements for guidance systems. Adverse environments and fire-and-forget capability were to be emphasized.

B. Extent of the Study

A literature survey indicated a limited number of reports discussing systems employing two or more wavelengths for specific tasks. The literature is more helpful in selection of wavelength regions where several relevant studies are reported. Analysis of conceptual systems is handicapped by the lack of useful data, particularly regarding coherent radiation and its interaction with typical targets and backgrounds. However, background measurements for both passive and active infrared systems are required in order that modern analysis techniques can be effectively applied to the problems of acquisition and guidanc'

Improving component technology will permit considerable sophistication in future seeker systems, and such sophistication may well turn out to be essential as target signatures become much more difficult to separate from background clutter and decoys. Limitations to our ability to model situations of interest to this study because of a lack of data are mentioned in several sections.

C. General Conclusions

Most dual wavelength systems described in the literature are of little value for the missile guidance and target acquisition problem where the target is likely to be imbedded in strong clutter. The combination of an active and passive system does offer a unique combination of advantages in contrast to other combinations of active-active and passive-passive systems. The characteristi:s of an active-passive system operating in the 8-14μm wavelength region are discussed. The desirability of this wavelength region and the favorable status of component technology for the avelength region make this an attractive alternative for seekers or trackers for missile guidance. The study also shows the strong need for more data on active signatures for both targets and clutter.

II. DUAL WAVELENGTH SYSTEMS

In order to better understand the possibilities offered by dual wavelength systems, several examples of such systems were reviewed. A brief summary of these systems is presented here. A more detailed discussion is presented in Section VII relative to combined active and passive systems.

A. Earth Observations

Multispectral systems are used by NASA for earth observation satellite measurements of passive radiation. The result is a set of data representing emitted and reflected radiation from terrain measured at discrete wavelengths over an extended wavelength region. The set of measurements, so called measurement vectors, is then used to provide a more reliable classification of the terrain feature than might be attainable from only one or two general wavelength measurements. Although great effort has been expended on analysis techniques, very little work has been done on the selection of wavelengths to be used for the initial measurements.

B. Metrology and Interferometry

In the fields of metrology and interferometry, multiple wavelength systems are used for absolute shape contouring and surface finish measurements where the object is large, or where the finish is rough or of complex shape. Two frequency holograms are range contours of the object with adjacent maxima or minima separated in depth by a distance of

$$D = \lambda_1\lambda_2/(1 + [1/\cos\alpha])(\lambda_1 + \lambda_2)$$

where λ_1 and λ_2 are the two wavelengths and α is the angle between the illumination and viewing directions.

An optical system such as a Michelson interferometer can be used to measure surface motion in a direction normal to the beam. One beam reflects off the surface of interest, the other reflects off a vibrating reference mirror. The interference between the two reflected beams leads to a time varying output photocurrent. The amplitude of the vibration may be extracted by amplitude modulation detection techniques. For nonsinusoidal motion at low frequencies, 1/f and other noise sources make detection difficult.

A two-frequency system recently described offers a means of circumventing this problem [1]. The system uses a He-Ne laser modulated to produce two closely spaced frequencies. A heterodyne detection system is used. The phase of the beat photocurrent caused by the two different frequencies is modulated by the motion of the surface being observed. The vibration amplitude is detected from the phase-modulated beat photocurrent by means of phase-demodulation techniques. By this technique, the low-frequency signal can be processed at a frequency shifted up by the carrier beat frequency. In this way, low frequency noise is eliminated. For stepwise oscillatory motion at 0.2 Hz, a minimum displacement of 2.9 Å was measured.

C. Radar Systems

In radar systems, frequency diversity has been used to reduce glint. Small changes in frequency from pulse to pulse produce reflections from a moving target which are uncorrelated with one another. Dual frequency Moving Target Indicator (MTI) systems have been studied with the general conclusion that any advantages to such a system are marginal.

Continuous wave radar systems can provide measurement of range by using a dual frequency system [2]. Two continuous waves with a small frequency difference, Δf, will have a relative shift in phase which increases proportionally to the distance traveled by the waves. At a distance R_O, the accumulated phase shift $\Delta\phi$ is given by

$$\Delta\Phi = 2\pi \ \Delta f \ R_O/c$$

where c is the velocity of the radar waves. In the case of reflection from an object at range R_O, the phase difference doubles as the returning waves reach the transmitter. A receiver can then determine the range by a measurement of the difference in phase of the two Doppler shifted waves. The range is given by

$$R_O = c\Delta\phi/4\pi\Delta f \ .$$

D. Military Systems

Several military systems using two or more frequencies are of potential interest. The following sections will consider some of these possibilities in more detail. The use of an active and passive infrared system is considered in Section V, while active infrared systems of more than one frequency are discussed in Section VIII.

Here we wish to briefly outline some possible advantages of a system combining passive infrared with a longer wave active system operating in the millimeter or submillimeter wavelength region. Component technology is reaching a level where systems of this type can be realized. During the next few years the performance of these systems will be evaluated and their potential value in military systems will be established. An incentive for this effort is the possibility of overcoming the disadvantages of infrared imaging systems by combining their advantages with the advantages of longer wavelength systems.

The combination system might consist of a Foward Looking Infrared (FLIR) and a millimeter wave radar operating at 70 GHz or 90 GHz boresighted on the same antenna pedestal. Some advantages of this combination would be the following:

1. The millimeter wave radar can be used to cue the FLIR which provides finer details useful for target recognition and identification.

2. The millimeter wave radar is more efficient for search, and for range determination than the FLIR.

3. The radar is more effective during adverse weather, particularly fog. The atmosphere is more transparent and less of a problem at millimeter wavelengths.

4. The effects of scintillation and glint are reduced at millimeter wavelengths.

5. The millimeter wave system will penetrate foliage and vegetation that will be opaque to infrared systems.

To combine adverse weather operation with reasonable resolution the radar could operate in the submillimeter wavelength region. A review of submillimeter technology, atmospheric effects, and system performance was prepared at Georgia Tech in 1976 [3]. Maximum range for target identification was tabulated for wavelengths in the atmospheric windows.

III. ACTIVE SYSTEMS WITH HETERODYNE DETECTION

In this section two examples of active systems will be covered in greater detail. The first is what might be called an active-active system in contrast to an active-passive system which appears to be the most useful. The second is a three-wave system proposed by Teich [4].

A. Active-Active Systems

Several examples of active systems operating in more than one mode have been considered. For example, beam rider systems using more than one wavelength for the guidance system offer certain advantages. A laser system emitting both a continuous wave and short mode-locked pulses simultaneously offers the possibility of obtaining both range (from the time delay of the pulse) and target velocity (from the Doppler shift of the continuous wave) [5].

The emitted wave amplitude will be of the form

$$E_T = E_M + E_C \quad \text{with}$$

$$E_M = \sum_{n=-N/Z}^{N/Z} A_n \exp\{2\pi L[(f_M + n\Delta f)t + \phi_n]\}$$

$$E_C = b \exp[2\pi L(f_C t + \phi)]$$

where f_M is the frequency of the central longitudinal mode,

$\Delta f = C/2Lm$ the frequency difference between successive longitudinal modes in in a cavity of length L,

ϕ_n is the phase uncertainty of the nth mode,

f_C is the frequency of the continuous wave, and

ϕ is the phase of the continuous wave with respect to the mode-locked wave at $t = 0$.

The amplitudes of the continuous wave and the components of the mode locked pulse are given by b and the A_n.

The potential resolution of the mode-locked waveform is L/2N. For an Yttrium Aluminum Garnet (YAG) laser, N can have a value of several tens. For a value of N = 25, and a cavity length of 0.5 m, a resolution of 1 cm is indicated. The limiting resolution in the frequency dimension is given by the reciprocal of the duration of the Continuous Wave (CW). For a value of 1 ms, a resolution of 1 KHz is theoretically attainable.

Analysis of the signal returned from a moving object shows the disadvantages of this system.

The phase uncertainties as characterized by the ϕ_n severely limit the frequency resolution of YAG mode-locked lasers. Phase stability over a period of 1 ms is not known. However, with an emitted wave form consisting of both a continuous wave and mode-locked pulses, the uncertainties of both wave forms are combined in the output signal. While the flaws add, there is little enhancement where the advantages overlap.

Thus the phase uncertainties in the mode-locked YAG laser pulse have the result that the capability of the coherently processed signal to measure the target velocity by a Doppler shift is reduced. Similarly any benefit to the system from the Doppler resolution provided by the CW laser is offset by a loss in range resolution caused by the addition of the CW laser's effect on the overall system uncertainty.

In addition to the ambiguity caused by the interaction of the phase uncertainties of the two waveforms, additional uncertainty in system resolution arises from speckle effects and from system noise. As a result of these problems, this particular bi-wavelength technique cannot compete with well-designed single laser systems.

B. Three-frequency Heterodyne System

The three-frequency heterodyne system proposed by Teich [4] is worth noting for its potential for certain systems containing an undetermined Doppler shift and for its immunity to countermeasures. The transmitter radiates two signals with a small but well-known frequency difference $\Delta\nu$. The receiver provides an output very close to $\Delta\nu$ regardless of the Doppler shift occurring in the received signal. Any other received signal not producing a receiver output near $\Delta\nu$ may be ignored.

If the two waves are taken to be ν_1 and ν_2, the frequency difference $\Delta\nu$ will not be significantly altered if the waves are Doppler shifted by reflection from a moving target. The shifted frequencies are given by the standard formula

$$\nu' = \nu(1 + 2v/c)$$

where v is the target velocity. After reflecting from the target, the new frequency difference is therefore

$$\Delta\nu' = \nu_1' - \nu_2' = \Delta\nu \pm (2v/c)\Delta\nu$$

In addition to the frequency shift, there will also be a broadening of the frequency of both waves associated with target properties and motion. In a practical situation, the frequency difference $\Delta\nu'$-$\Delta\nu$ will be much smaller than the broadening effects and may usually be neglected ($v<<c$).

Heterodyning the signal with a local oscillator (LO) of frequency ν_L creates signals at ν_1'-ν_L and ν_2'-ν_L. The output is coupled to a second detector through a filter of bandwidth Δf. The second detector then produces an output at approximately $\Delta\nu$. Its frequency response must extend only over the bandwidth Δf, and its output is independent of the stability of the Doppler and the LO frequencies. A low noise bandwidth can then be attained using a narrow band filter centered near $\Delta\nu$ after the second detector.

The signal-to-noise ratio for the three-frequency heterodyne system has been calculated for several cases of interest. Of particular interest is the situation where $P_r/\Delta f<<h\nu/\eta$.

Here P_r is the power of the received signal, $h\nu$ is the photon energy, and η is the quantum efficiency of the heterodyne detector. For this weak signal case

$$\mathrm{SNR} \approx (\eta P_r/\sqrt{3}\, h\nu)^2/B\Delta f \; .$$

For the minimum detectable power P_r (min), the SNR is taken to be SNR = 1 yielding

$$P_r(\mathrm{min}) \approx (\sqrt{3}\, h\nu/\eta)(B\Delta f)^{1/2} \; .$$

This result may be compared with the equivalent quantity for a conventional heterodyne detector using photoconductive or biased photovoltaic detectors.

$$P_r'(\mathrm{min}) = 2h\nu B/\eta \; .$$

The improvement in SNR is given by the ratio

$$\mathrm{SNIR} = (2/\sqrt{3})(B/\Delta f)^{1/2} \; .$$

Let us consider the application of this three-frequency system to a missile seeker application. We take as an example a missile launched from a helicopter with a velocity of 1300 ft/second. Using the equation for Doppler, one finds that a laser and heterodyne receiver system in this missile will require about a 70 MHz receiver bandwidth when observing a stationary target. The full bandwith is required because the missile slows during flight and the Doppler shift decreases.

For a conventional heterodyne system, the minimum detectable power will be

$$P_r'(\text{min}) = 2.6 \times 10^{-12}/\eta \text{ (watt)}$$

for the three-frequency system

$$P_r(\text{min}) = 8.6 \times 10^{-15}/\eta \text{ (watt)} \quad .$$

We assume a CO_2 laser is used, and that $\Delta f = 1$ kHz. In this case, the improvement using the three-frequency system is

$$\text{SNIR}=300, \text{ or } 23 \text{ dB.}$$

A CO_2 laser can be modulated to produce two frequencies, or can be designed to oscillate in two modes simultaneously. Stabilization will be required. The improvement possible for specific systems must be weighed against the possible complications introduced by a somewhat more complex three-frequency heterodyne system.

C. Vulnerability and Countermeasures

Active military systems have an inherent disadvantage over passive systems because the emitted energy provides a means of locating the signal source. For the case of the CO_2 laser as the source, the disadvantages are mitigated for several reasons. These are the following:

1. Scattering is greatly reduced at 10.6μm compared to 1.0μm. Detection of off-axis scattered radiation is much more difficult.

2. Cooled detectors must be used for sensitive detection systems which increases their cost and complexity.

3. Detection systems must operate with large Fields-of-View (FOV) for efficient coverage of large solid angles. The FOV of the active system can be orders of magnitude smaller. The advantage of the target which receives a higher field strength than the colocated receiver is greatly reduced or eliminated.

4. Range gating and Doppler effects can be used in coherent receiver to reject countermeasure signals and enhance the effectiveness of the system.

As will be discussed, the range gate provides rejection of flares and fires by requiring a close facsimile of the original pulse in the return, which would not be present from a nearly constant amplitude flare.

IV. CHOICE OF WAVELENGTH

In terms of current technology, the CO_2 laser is the only suitable laser that can be considered for military systems in the wavelength region beyond the near infrared. Not only does it operate in a region of good atmospheric transparancy at 10.6 μm, it is also very power effecient in comparison to other lasers and can be so constructed as to occupy a volume of a few cubic inches.

Thus one is led to consider systems operating in the 8-12 μm atmospheric window. This is the wavelength region used by the common modular FLIR. This wavelength region is considered to be preferable to the 3-5 μm atmospheric window for night vision systems, although recent studies now suggest that the question is not as clear cut as previously believed [6,7]. For this reason, a short review of the relative advantages and disadvantages is in order.

The comparisons tend to develop a ratio of the performance of a modern FLIR operating in the 3-5 μm (sw) band to the performance of a modern FLIR operating in the 8-12 μ (lw) band. By a modern FLIR, one means that performance is not limited by technology problems such as detector cooling or low quantum efficiency.

The mathematical expressions for performance estimates are the following [8]. The performance index of a system is taken as

$$R'_{\Delta d} = k\eta_d \sqrt{\eta_q}\ R_{\Delta T}$$

where

$k = 1$ for photoconductive detectors and for photovoltaic detectors,

η_q is the detector quantum efficiency,

η_d is a detector size parameter, and

$R_{\Delta T}$ is a radiation function given by

$$R_{\Delta T} = \frac{1}{2\sqrt{2hc}} \frac{\int_0^\infty \tau_f(\lambda)\tau_a(\lambda)(\partial^2 J_t/\partial T\partial\lambda)\lambda d\lambda}{[\int_0^\infty \tau_f(\lambda)\ L_b^*/\partial\lambda d\lambda]^{1/2}}$$

where $\tau_f(\lambda)$ is the transmission of the filters and optics,

$\tau_a(\lambda)$ is the transmission of the atmosphere

J_t is the target radiant intensity, and

L^*_b is the background radiance.

The radiance and radiant intensities are in units of photons/m^2 sec str.

The numerator of the expression for $R_{\Delta T}$ is a measure of the signal for small excursions of the target temperature from the background. The denominator is a measure of the background noise.

With modern technology (exceptional detectors) there are only two major considerations, the atmospheric transmission and the modulation transfer function of the optics (MTF). Because of the shorter wavelength, the system operating in the 3-5 μm wavelength region has an advantage in resolution for a fixed aperture size.

Tuer [6] included both terrain radiance and atmospheric path radiance (simultaneous absoption and emission along each segment) in calculating background radiance L^*_b. Relative performance was determined for a tank target. His results were as follows.

For the conditions assumed in the calculations (rear aspect tank target long path lengths, low altitude, high humidity, Lowtran III atmospheric model) the SW (3-5) was superior to the LW (8-12) region at most operating conditions. The superiority increases with range. At a range of 20 km, the short wave (SW) system has about an order of magnitude better performance for summer conditions and about two orders of magnitude better performance for tropical conditions. For winter (dry) conditions, performance of the two systems is comparable to within typically 30 percent over path lengths from zero to 20 km. The SW system is slightly better at short ranges and slightly worse at other than a rear aspect. The long wave (LW) system performance becomes inferior at short ranges for the summer atmosphere and for tropical conditions. Also, the SW system then becomes inferior to the LW system at short ranges for cooler targets.

Milton, Harvey, and Schmidt [7] find that the LW system is superior at short ranges for targets 1 degree C different than the background. At longer ranges, beyond 20 km for a maritime atmospheric model, the SW system has a higher signal-to-noise ratio. As humidity increases, the crossover range is reduced.

In general, high humidity tends to penalize the LW system, while scattering from haze, dust, and smoke tends to penalize the SW system.

These two reports are relatively recent but do not draw the same conclusions. What is evident from both reports is that any comparison of FLIR systems in the SW (3 μm-5 μm) and LW (8 μm-12 μm) bands is controlled by the model used for atmospheric transmission. In the opinion of the authors, present models are not sufficiently reliable to permit unambiguous conclusions to be drawn. The question will surely be considered in further studies.

From the point of view of tactical systems operating at ranges of 5 km or less, it appears that the LW systems are preferable. This conclusion is strengthened when the possibility of operating in a battlefield atmosphere filled with smoke and dust is considered. Under these conditions, relative performance of the LW system is enhanced.

No reports were found that included effects due to background clutter in the analysis. Such effects will be considered in the next section.

V. EFFECTS OF CLUTTER

There are several reasons for the selection of the 8-14 μm spectral region for FLIR systems. Atmospheric transmission was believed to be much better, and terrain radiance is at

its maximum. While the atmospheric transmission consideration is not amenable to a simple answer for all situations, the variation of terrain radiance with temperature and emissivity does attain maximum values in this region for objects near ambient temperature. *Table 1* shows values of normal radiance of black bodies in the two wavelength regions of interest for several temperatures. Up to temperatures of over 500 degrees K the long wave infrared region has greater radiance.

The derivative of radiance with temperature is also listed. Near ambient temperature, radiance in the long wave region shows almost ten times the variation with temperature as radiance in the short wave region. As a result of such sensitivity, small variations in temperature or emissivity will be seen in FLIR systems with the maximum clarity possible by choosing the 8-14 μm region. The scene being viewed will more closely resemble the same scene in natural light, and targets can be recognized quickly without extensive training.

A small change in emissivity is equivalent to a small change in the fraction of radiant energy emitted. The $\Delta\epsilon$ equivalent of a one degree temperature change is shown in *Table 2*. The smaller values for the long wave infrared region indicate that smaller changes in emissivity caused, for example, by small amounts of surface oxidation or dust will be as significant as a one degree temperature change. These considerations suggest that radiance in the long wave infrared region will have much of the texture and detail of the same scene viewed in reflected daylight. The human observer is accustomed to high levels of background clutter and can detect targets in a relatively noisy scene. Current FLIR systems can be very effective for target acquisition under appropriate conditions. The same technology can lead to problems for automated acquisition systems as considered in this report.

Automated systems depend in large measure on contrast between target and background. In *Table 3* and *4* the reflectivity ρ and emissivity ϵ ($\rho = 1 - \epsilon$) for several materials of interest are compared. Contrast in $\rho^{1/2}$, appropriate to coherent systems, is also listed.

Unfortunately, these data are few in number and may well be unrepresentative or misleading. The data needed for detailed study are nonexistant. Present data in *Tables 3* and *4* suggests that contrast in coherent systems should be sufficient for a useable system but superiority of one target detection system or wavelength region over another cannot be clearly discerned. For comparison, contrast in emissivity is presented in *Table 5* for the same backgrounds.

In general, it appears that cultural objects have higher reflectivities at 10.6 μm than do natural objects. Thus, background and clutter may be expected to be less significant for a

TABLE 1. COMPARISON OF THE RADIANCE OF A BLACKBODY SURFACE AND ITS TEMPERATURE DERIVATIVE INTEGRATED OVER TWO SEPARATE WAVELENGTH REGIONS FOR TEMPERATURES OF INTEREST.

	TEMPERATURE	WAVELENGTH BAND		RATIO
	°K	3-5 μm	8-12 μm	β(8-12μm/(β(3-5μm)
Radiant Emittance W/ Π in W/cm^2	300	1.873 10^{-4}	3.852 10^{-3} w/cm^2	20.6
	400	9.466 10^{-4}	4.231 10^{-3}	4.5
	500	167.7 10^{-4}	28.955 10^{-3}	1.7
Temperature Derivative $\partial W/\Pi \partial T$ in W/cm^2	300	0.679 10^{-5}	0.630 10^{-4} w/cm^2°k	9.3
	400	6.35 10^{-5}	1.27 10^{-4}	2.0
	500	23.5 10^{-5}	1.83 10^{-4}	0.78

TABLE 2. EFFECT OF A 1° C TEMPERATURE CHANGE

THE LOG DERIVATIVE $\Delta W/W\Delta T$		
EQUIVALENT $\Delta\epsilon$ $\Delta W/W\Delta T$	3-5 μm REGION	8-12 μm REGION
At 300 °k	0.036	0.016
400°k	0.067	0.030
500 °k	0.014	0.006

TABLE 3. REFLECTIVITY AND EMISSIVITY VALUES

BACKGROUND MATERIAL	3-5 μm REGION			8-12 μm REGION		
	ρ	$\sqrt{\rho}$	ϵ	ρ	$\sqrt{\rho}$	ϵ
Sand-Silt Loam	.26	.51	.74	.07	.26	.93
Bark-Colorado Spruce	.13	.36	.87	.06	.24	.94
Asphalt Road	.28	.53	.72	.08	.28	.92
Coal Tar Pitch	.08	.28	.92	.12	.35	.88
Olive Drab Paint on steel	.38	.62	.62	.13	.36	.87

Reflectivity and emissivity variations among materials of interest. Data from "Handbook of Infrared Technology", ONR, US Government Printing Office, 1965 and "Reflectivity Measurements with 10.6 μm Infrared Radiation". G.E. Vandamme and M.J. Amoruso, Army Weapons Command, June (1972) AD-746-238.

TABLE 4. POWER AND AMPLITUDE AND REFLECTIVITY CONTRAST.

CONTRAST COMBINATION	3-5 μm REGION $\sqrt{\rho_T} - \sqrt{\rho_\beta}$	$\rho_T - \rho_\beta$	8-12 μm REGION $\sqrt{\rho_T} - \sqrt{\rho_\beta}$	$\rho_T - \rho_\beta$
Olive Drab Paint on Steel				
vs. Spruce Bark	0.26	0.25	0.12	0.07
vs. Asphalt Road	0.09	0.10	0.08	0.05
vs. Silt Loam	0.11	0.12	0.10	0.06

Contrast in reflectivity between olive drab paint on steel and typical backgrounds.

TABLE 5. CONTRAST IN EMISSIVITY.

CONTRAST COMBINATION	3-5 μm REGION $\epsilon_T - \epsilon_\beta$	8-12 μm REGION $\epsilon_T - \epsilon_\beta$
Olive Drab Paint on steel		
vs. Spruce Bark	-0.15	-0.07
vs. Asphalt	-0.10	-0.05
vs. Silt Loam	-0.12	-0.06

Contrast in Emissivity between olive drab paint and some typical backgrounds.

coherent system than for a passive FLIR system. The implication is that automatic target acquisition may be an easier task with a coherent system viewing the same scene than for a passive system. The advantage may be more significant for future systems where thermal target signatures could be greatly attenuated making acquisition by passive systems a formidable problem. For this situation, the advantages of a coherent system could be emphasized helping to make its disadvantages more acceptable. These considerations would be valid both for situations where the seeker was assisted in locating the target during the initial phase of the acquisition process (look before launch) and situations where the seeker selects the most promising target within its scanfield (indirect fire).

The limited amount of information in the archive literature suggests that clutter in the 8-14 μm band is higher than clutter at shorter wavelengths [9]. These results are in agreement with the general considerations previously discussed, and raise the following question.

Does the higher clutter noise and higher photon noise (resulting in smaller D*) for the 8-14 μm spectral band place this band at a relative disadvantage compared to other bands at shorter wavelengths?

This is not quite the same question discussed in connection with FLIR systems, because with FLIR systems the human observer is accustomed to identifying targets in a cluttered scene. The question is not easily answered, depending as it does on backgrounds, targets, the atmosphere, and component status.

The clutter background will determine the effectiveness of a seeker system. The spectral distribution of clutter (in c/rad) is usually similar to Gaussian, often with the addition of some anomalous objects that do not conform to a Gaussian distribution. If large areas of the background are different in nature (such as trees, bare ground, grassy fields), the clutter spectra resemble a multi-model Gaussian distribution with each region having its own distribution about its own mean temperature.

Further, the distribution changes with the season, the time of day, and the weather. Clutter is reduced in wet weather conditions (along with most infrared target signatures). Setting a seeker to look for a target assuming either average, maximum, or typical clutter spectra risks a substantial degradation in performance when background conditions differ.

What is required is a seeker that adjusts its target selection algorithm to account for the background clutter within its field-of-view. This could be accomplished during the first few scan lines or during the initial readout of a staring focal plane. A complete discussion of this approach to seeker design is beyond the scope of this report. Further, the effectiveness of a

specific approach is difficult to quantify because the necessary details of background clutter and target properties cannot be modeled reliably without additional measurements.

While several decision criteria may be considered for implementation in a sensor, and many can guarantee a very small probability that a particular fluctuation in background radiance will be falsely identified as a target, the sensor may examine thousands of scene elements during a target search. Thus the overall probability of false detection may become unacceptably large.

Despite the severe problems, we expect future seekers to incorporate adaptive features to accommodate varying backgrounds and target characteristics.

VI. MISSILE GUIDANCE

Two-color seekers with adaptive processing as previously described offer strong potential for a fire-and-forget missile or indirect fire systems. A second color provides an additional source of information or an additional mode of operation to aid the solution of the target identification and range closure problem.

Two types of sensors may be considered. A typical two-color seeker should respond to two separate wavelength regions. We also consider an active seeker as a pseudo two-color seeker for it should be possible to permit the seeker to operate in a passive mode thus obtaining different information which may be necessary during range closure. We discuss these two types of sensors in turn.

The two-color approach to target discrimination offers a means of directly separating targets from false targets such as sun glint, flares, fires, burning vehicles, or gunfire flashes. The system can reject such scene elements and concentrate on the task of separating scene clutter from real targets. Decision theory will be an essential part of the system along with an adaptive technique for minimizing background effects.

The output from the sensor, once the target has been selected, will become stronger during range closure. The signal-to-clutter ratio will not improve except that as the target begins to fill the sensor field-of-view, the scene statistics change. Selecting the warmest point in the scene should be a satisfactory criterion for the terminal phase of the flight.

An active seeker may have a more difficult task during range closure. It may be desirable for an active seeker to select a strong glint, a centroid of a glint group or a

combination of glint plus other information as the target. The other information could include Doppler or vibration signatures as well as surface reflectance and spatial properties. During range closure, the solid angle subtended by the target increases and the glint pattern should change. Toward the end of the flight path, rapid changes in the pattern may be anticipated.

Now, the foregoing is all speculation. The appearance of targets and background clutter to an active seeker has not been established. No accepted method exists for calculating performance. If the appearance of the target changes rapidly, it may be necessary to switch off the active laser and use the detector in a passive mode. It is usually possible to make this change because the optics and mechanical structure are compatible with a passive system. Some switching in signal processing may be required.

Several possible criteria could be used to determine when to change modes in order to use a thermal signal for terminal homing. It is assumed that a CO_2 laser at 10.6 μm is used as the active source, and that a narrow spectral band centered about this wavelength is used to receive the passive signal.As discussed earlier, for the short ranges appropriate to ground engagements and typical battlefield conditions of smoke, dust, and haze, this wavelength region is to be preferred.

With the target centered during range closure, a switch to the passive mode could be made when the apparent shift in target centroid exceeds a preset rate. Alternatively, when the peak glint signal exceeds a preset threshold for several successive scans or a preset number of times in a single scan, a change in mode could be made. A decision based on sampling the incoming data stream should be more suitable than arbitrary switching based on, for example, time of flight.

This problem, range closure for active seekers, must be studied in more detail. In particular, data on the appearance of backgrounds and targets to reflected radiation at 10.6 μm is essential. Without such information, all attempts to model seeker and guidance behavior cannot be considered reliable. Range closure problems specific to combined active and passive systems are discussed in Section VII.

It is worth noting that the technology needed to implement systems discussed in this study is largely available for the 8-14 μm region. The CO_2 laser-HgCdTe detector chain represents the important element in these systems. Specific variations of these components will be required to meet systems specifications. However, the problems are those of engineering development and production engineering.

Such a satisfactory situation does not exist for the 3-5 μm region where the lack of an efficient radiation source presents a significant problem for systems applications. No efficient laser corresponding to the CO_2 laser has been developed.

The present status of technology and components adds to the weight of other considerations suggesting that the 8-14 μm be emphasized in advanced systems development.

VII. COMBINED ACTIVE AND PASSIVE SYSTEMS

A. Introduction

Combined active and passive systems offer the potential for cost advantages over other dual systems (two-color passive or dual frequency active). In addition, the unique combination of an active channel combined with a passive channel can provide new and powerful discrimination capabilities not obtainable with other combinations or single mode systems. This section examines two general classes of active/passive systems: single detector systems and dual detector and/or optic systems.

The first class of systems addresses the question of whether an active illuminator can be combined with either an existing passive system or a newly designed passive system to provide enhanced discrimination capabilities with moderate cost increases for retrofits and use of current technology.

The discussion of the second class of systems assumes that with current technology, more or less standard designs for separate active and passive subsystems can be combined. Potential uses for such systems are determined by examining the intrinsic properties of targets, backgrounds, clutter and countermeasures and their effects on each subsystem and on the combination. The results of this study indicate several discrimination schemes are possible, provided much more data on active signatures for both targets and backgrounds can be gathered.

B. Single Detector Systems

In previous studies by groups at MICOM as well as other locations, the advantages of the 8-14 μm region relative to other atmospheric windows have been emphasized. The considerations include atmospheric characteristics, component technology, vulnerability, countermeasures, and system performance. Therefore the emphasis in this section will be on a 10.6 μm CO_2 laser combined with an 8-14 μm FLIR. The most obvious advantage for such a

combination is that potentially, the optics, detector, and processing electronics can be common to both the active and passive portions of the system. This presents immediate advantages which would minimize cost increases during conversion from single mode systems. Such upgrades could be in the form of a retrofit of active illuminators to currently existing FLIR systems. Alternately, new compact designs could be implemented to optimize the interface between the two systems. To get a better idea of what requirements for such systems are, an expression for the ratio of irradiance due to the active system to the irradiance from the passive system will be derived.

C. Active to Passive Ratio (APR)

The ratio of active to passive irradiance is the most useful of possible parameters in that it is nearly independent of system specifics (except for instantaneous field-of-view and laser power). Thus the basic requirements can be examined with few restrictions on systems to determine the theoretical implications of combined systems. By choosing irradiance at the seeker aperture, general conclusions derived from the APR can be quickly related to real systems through noise equivalent flux density (NEFD) measurements or calculations.

For a passive system, the scene radiance from a target and background of area A_T and A_B with emissivities ϵ_T and ϵ_B will be

$$N_P = [A_T(\varepsilon_T W_T - \varepsilon_C W_C) + \varepsilon_C W_C A_B]/\pi A_B$$

in watts/cm^{2}sr where W_T and W_c are the radiant intensities of the target and background in watts/cm^2. The irradiance at the seeker will be given by

$$H_P = [N_P(\mathrm{FOV})^2 \exp -\alpha R]/\pi \text{ in watts/cm}^2$$

where FOV is the seeker field-of-view, R is the range, and α is the atmospheric attenuation per unit length.

For an active system, the power in the laser beam at the target is given by $P_o \exp -\alpha R$ where P_o is the power in watts for the unattenuated beam. The reflected energy is equavalent to a scene radiant intensity of

$$\bar{W}_a = (\rho_e P_o \exp -\alpha R)/A_B \text{ in watts/cm}^2$$

where A_B is the area illuminated by the laser and ρ_e is an effective reflectivity given by

$$\rho_e = [A_T(\rho_T - \rho_c) + \rho_c A_B]/A_B$$

where A_T and A_B are target and background areas as previously defined, and ρ_T and ρ_c are the target and background reflectivities.

As in the passive case, the irradiance at the seeker will be given by

$$H_a = \bar{W}_a (FOV)^2 \exp -\alpha R \text{ in watts/cm}^2.$$

The APR then becomes

$$APR = \frac{P_o[A_T(\rho_T - \rho_c) + \rho_c A_B]\exp -\alpha R}{[A_T(\varepsilon_T W_T - \varepsilon_c W_c) + \varepsilon_c W_c A_B]A_B}.$$

D. Power Requirements

To determine what kind of ranges are possible with currently available small CO_2 lasers, the following assumptions are made: the target is greater than or equal to the beam diameter, and the range is calculated with an APR equal to one. Initially we assume no atmospheric attenuation to determine maximum effective ranges. Once approximate ranges have been determined, atmospheric effects are then added to show how much maximum range is reduced by inclement weather.

Under the preceeding assumptions, the expression for APR reduced to:

$$APR = \frac{P_o \rho_T}{A_B \varepsilon_T W_T}.$$

The area of the beam at the target is given by:

$$A_B = \frac{\pi}{4} (FOV)^2 R^2.$$

making the substitution for A_B and rearranging terms, the range can be determined from:

$$R^2 = \frac{P_o \rho_T}{APR\ (FOV)^2 \varepsilon_T W_T}.$$

Currently available small to medium size pulsed lasers have average powers of 100 mW to 10 W with pulse widths of 100 nsec to 1 μsec. If the pulse repetition frequency (PRF) runs from 10 Hz to 10 kHz, laser peak powers *run from 10 W minimum* to 10 MW (1 joule) maximum. For a target with an apparent average temperature of 350 degrees K the total radiant intensity over the 8-14 μm band is 26 mW/cm^2. *Table 6* shows ranges for the indicated powers assuming the target has a diffuse Lambertain reflectivity of 10 percent.

In order to determine how this relates to typical real systems, NEFD was calculated for several configurations. The NEFD is given by:

$$NEFD = \frac{4B^{1/2} FOV\ F\#}{\tau_o D_o D^*}$$

where $B^{1/2}$ = square root of electronics noise bandwid'h
FOV = seeker field-of-view
F = f-ratio of optics
τ_o = transmission of optics
D_o = diameter of optics
D^* = detector detectivity

The diameter of the optics runs from 3 to 12 inches; D^* from 10^9 to 5×10^{10} cm Hz$^{1/2}$/W; B = 20 kHz to 100 kHz; FOV = 1 mrad; f = 1.5 to 3. *Table 7* shows NEFD for each of the standard aperture diameters for an F/2 system with a 20 kHz bandwidth and D^* of 5×10^9 cm Hz$^{1/2}$/W. Thus the NEFD's *run from* 10^{-11} *W/cm^2 to* 4×10^{-11} W/cm^2.

Table 8 shows radiant intensity as a function of temperature. Also shown is the irradiance H_o at the aperture of a seeker with a field-of-view of one mrad. To determine the maximum permissible atmospheric attenuation, the value of transmission which reduces the aperture irradiance to the NEFD found previously is determined. H_o ranges from 1.3×10^{-5}

TABLE 6. MAXIMUM RANGE FOR APR = 1

LASER POWER	MAXIMUM RANGE
1 MW	7.85 km
100 kW	2.47 km
10 kW	782.00 m
1 kW	247.00 m
10 W	17.50 m

TABLE 7. NEFD FOR AN F/2 OPTICAL SYSTEM WITH 20 kHz BANDWIDTH AND D* = 5 x 10^9 cm Hz 1/2 WATT.

DIAMETER OF OPTICS	NEFD
3 inch	3.71×10^{-11} watts/cm^2
6 inch	1.86×10^{-11}
10 inch	1.11×10^{-11}
12 inch	9.28×10^{-12}

TABLE 8. RADIANT INTENSITY AND IRRADIANCE

TEMPERATURE	W (8-12.5 μm)	H_O
300°k	13.5 MW/cm^2	1.35×10^{-8} w/cm^2
305°k	14.6	1.46×10^{-8}
310°k	15.7	1.57×10^{-8}
350°k	27.0	2.70×10^{-8}

W/cm^2 to 2.7×10^{-8} W/cm^2. This corresponds to a product of range and attenuation coefficient (αR) of from 5.784 to 7.901. *Table 9* shows maximum attenuation coefficients for the indicated ranges and a target temperature of 350 degree K.

TABLE 9. MAXIMUM ATTENUATION COEFFICIENT FOR INDICATED RANGE

RANGE km	ALPHA km^{-1}
1	7.9
2	4.0
5	1.58
7	1.129
10	0.7901

E. Range Closure

A primary problem associated with a single detector system is that, although laser power may be matched to the passive signal at a given range, the APR increases proportionaly to $1/R^2$ on range closure. Thus the detector is saturated quickly upon range closure. Two possible solutions exist: First, the system can be designed to operate over only very specific ranges. For instance it may be designed to operate from 2 km to 6 km, where the R^2 increase is only a factor of 9. Alternately, range may be extended by using the laser at full power only at maximum range. As the seeker range closes, laser power could be reduced to maintain a constant APR, using the pulsed lidar determination of range to determine an optical automatic gain control (AGC). This could be accomplished through either reducing the excitation voltage or by operating an electrically controlled optical attenuator. Reduction of excitation voltage could be used in conjunction with a scheme under which terminal homing is accomplished by the passive system only to avoid confusion created by multiple glints from the target due to the active illumination.

VIII. DUAL WAVELENGTH SEEKERS

A. Introduction

Three options are available in the organization of dual wavelength seeker systems. The first, a single detector combined active/passive system, has potential problems with differences in power levels between the two channels – differences which affect internal

scattering and detector saturation. The use of separate optics and detectors for each channel is a second option, one which allows the optimization of each channel but introduces problems with synchronization and spatial registration. A third approach employs separate detectors while providing for shared optics and scanning mechanism. Regardless of the concept chosen, however, the ultimate function of the seeker is to distinguish true targets from general background, clutter, and countermeasures. The methodology used in two-color passive IR systems is pertinent in such discrimination, as will be shown below. Nevertheless, the radically different information obtained from an active channel provides unique and improved discrimination, and this makes a combined system more desirable.

B. Two-Color Discrimination

Discrimination generally involves data remotely sensed from different classes of objects, such as grass, trees, rocks, tanks, flares, etc. Each sampled data point is classified according to differences in the incoming data. For example, the scanning of a scene containing only trees and tanks might produce a histogram similar to that shown in *Figure 1* for a particular color band. In single channel systems, a threshold or adaptive threshold algorithm is implemented (see *Figure 2*). A level is chosen as a threshold; any point with an intensity above this threshold is considered a target, while anything below the threshold is considered background. Two areas representing system errors are: the area under the background curve and above threshold, which represents the number of false alarms, and the area under the target curve and below threshold, which represents the number of target points missed. Usually, this error is measured by the area under the target above the threshold, which is the probability of detection. Beyond this simple process, and aside from sophisticated spatial discrimination, little more target recognition can be achieved.

Two-color passive systems, however, while retaining simplicity, can provide more precise detection. The intensity of a series of points in one passive channel versus that in a second independent channel has been plotted in *Figure 3*. In this two-color diagram, the lines labelled A1 and A2 correspond to thresholds set as if the two systems were independent. The simplest enhancement available to two-color systems is a requirement that a point be above threshold in both channels simultaneously. Such an area corresponds to the upper right quadrant of the lines A1 and A2.

A linear combination of intensities from channels 1 and 2 produces a "decision" function like that of line B. Several theorems are available which optimize the form of the combination (feature extraction). Lines C1 and C2 correspond to a constant ratio between channels 1 and 2. Curve D is typical of a statistically derived decision function which assumes

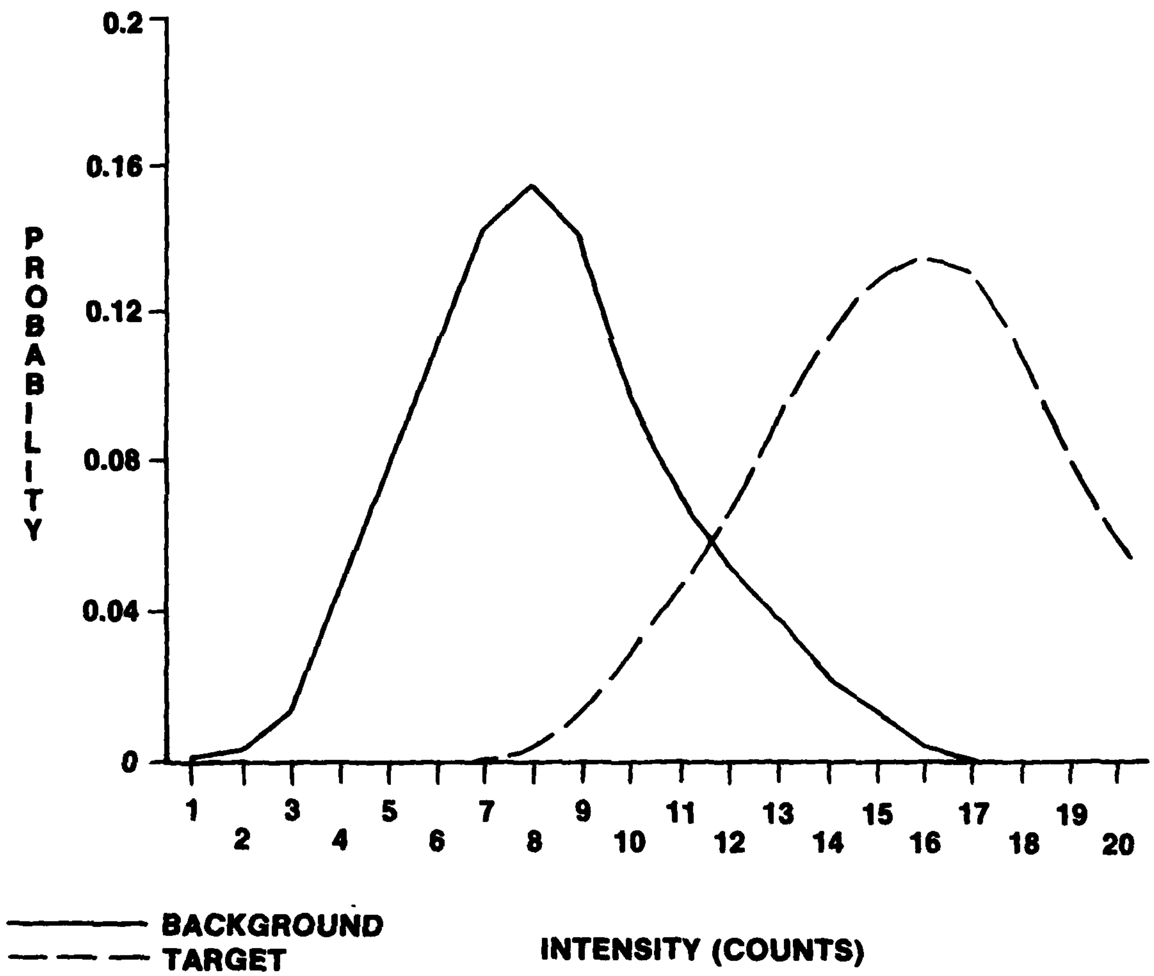

Figure 1. Single band probabilities.

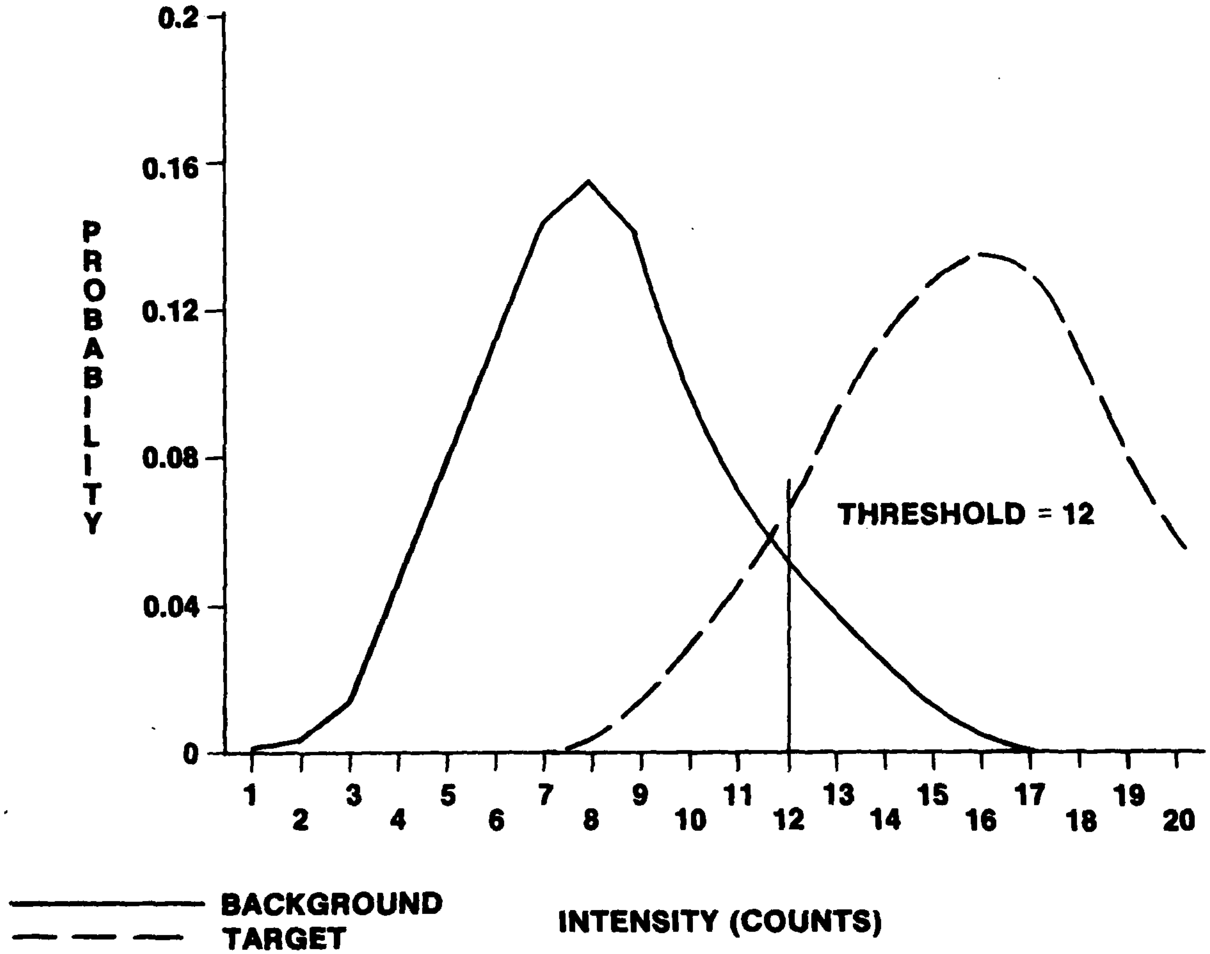

Figure 2. Threshold discrimination.

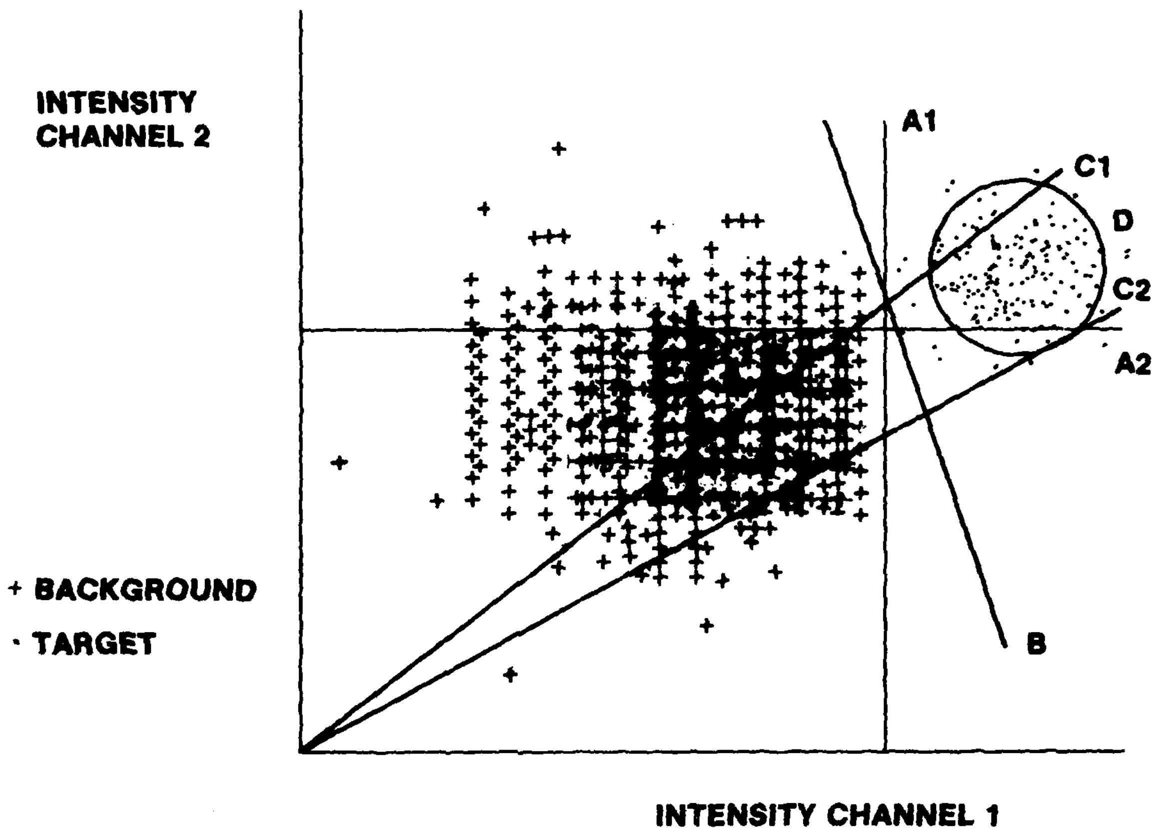

Figure 3. Two-color diagram.

that intensities of the classes to be separated are distributed as a Gaussian function of two variables (maximum likelihood). This last method usually provides a high probability of detection with the lowest possible false alarm rate. However, the algorithms for such a discrimination are complex and can exact a toll in required hardware.

The primary problem with two-color passive systems is that since both systems are passive, no range information is readily available and no estimation of current atmospheric effects can be made. A choice of spectral bands which provide sufficiently different information, and therefore offer more exact discrimination, is also a problem; too great a separation between bands may require separate optical systems.

C. Combined Systems

Combined active/passive systems can overcome some of the problems inherent in two-color passive systems. An active system can easily provide range and hence an estimate of current atmospheric attenuation. Furthermore, active and passive channels offer radically different signatures, even while operating in the same band. An investigation of physical properties of typical targets and backgrounds demonstrates how discrimination may be obtained in such a combined system.

An examination of the expressions for aperture irradiances for the active and passive systems, with the target (or clutter only) filling the instantaneous field-of-view, yields the following forms:

$$H_{active} \approx \rho_T P_O \exp(-2\alpha R)/R^2$$

$$H_{passive} \approx \varepsilon_T W_T (FOV)^2 \exp -\alpha R \ .$$

These may be broken down further:

$$H_a \approx [P_O][\frac{e^{-2\alpha R}}{R^2}][\rho_T]$$

$$H_p \approx [FOV^2][e^{-\alpha R}][\varepsilon_T W_T] \ .$$

In each case, the quantity in the first brackets is a property of the particular seeker configuration. The second term is a function of the scenario (atmosphere and range). The third is a function of the intrinsic properties of targets, clutter and countermeasures.

Due to the extremely limited amount of data available on active signatures, certain assumptions were required in order to calculate further. Some data are available on passive emissivities and/or reflectivities for certain materials. Most of these materials are opaque at infrared frequencies so that emissivity (ϵ) may be related to the Lambertian reflectivity (ρ) by Kirchoff's law based on conservation of energy or:

$$\rho = 1 - \varepsilon .$$

For metallic objects which have a strongly directional (specular) component, this assumption can be violated. The effects of this are discussed later but in essence these specular reflections are more useful than harmful for acquisition and tracking.

Table 10 shows a list of various materials and their emissivities and reflectivities obtained from two editions of the Military Infrared Handbook as cited with *Table 3*. It can be

TABLE 10. MATERIAL REFLECTIVITIES

	REFLECTIVITY
METALS	
Polished	.84-.95
Oxidized	.15-.45
GALVANITE	.43
FIBERGLASS	.25
OIL PAINT	.18-.63
MIL GRAY PAINT	.05-.17
ASPHALT	.08-.10
GLASS	.06
BRICK	.07
CONCRETE	.10-.18
PLASTER	.09
WOOD	.10
ROCK	.02-.40
GRASS	.12
SAND	.02-.08
LEAVES	.03-.10
WATER-ICE	.04
SNOW	.15

seen that metallic objects have reflectivities significantly different from nearly all other objects, including concrete, asphalt, and sand. Rocks, which are similar to lower reflectivity metals, stand closest to typical targets. *Figure 4* shows these objects plotted in descending order of reflectivity, with an indication of the variance for the class.

The passive signatures are calculated by integrating Planck's Law for blackbody radiation over the spectral band from 8 to 14 μm for varying temperatures. *Table 11* shows radiant intensities for various temperature blackbodies. *Table 12* is a list of objects showing their temperature, emissivity, radiant intensity, and radiance of an area of the object equal to that of a target (except for the flare). When these are plotted in a two-color diagram (see *Figure 5*), even more separation between targets and clutter is observed. The product W has been plotted because there is no practical way to determine them separately (this will be discussed later).

Most of the clutter, both natural and man-made, is clustered in the region of the low reflectivities; the power involved here is about 15 mW/cm^2. The target body lies well separated from everything except rocks for low signatures. In actuality, the situation is somewhat better in that the reflectivities for rocks are derived from band averages for emissivity. Many of the rock's spectral signatures show either sharp dips or below-average reflectivities at 10.6 μm when compared to band averages.

Flares, fires and the hot exhaust lie off scale vertically due to their extremely high passive signatures. Specular returns would lie off to the right of the normal target returns, but the passive channel would be little different. These results provide several opportunities for simple but effective discriminants.

D. Discriminants

Because of the overlap in passive signatures, application of simultaneous thresholds would not provide much more effectiveness than a single channel active system. *Figure 6* shows several potentially useful simple discriminants. Curve A is a linear combination of active and passive systems. Rejection of flare could be enhanced by adding a threshold in the active channel (line B) in combination with discriminant A. The third curve, C, is a constant product of the two channels and appears to be most effective. An additional rejection of flares and fires could be achieved by rejecting any return which did not have the proper pulsed return waveform.

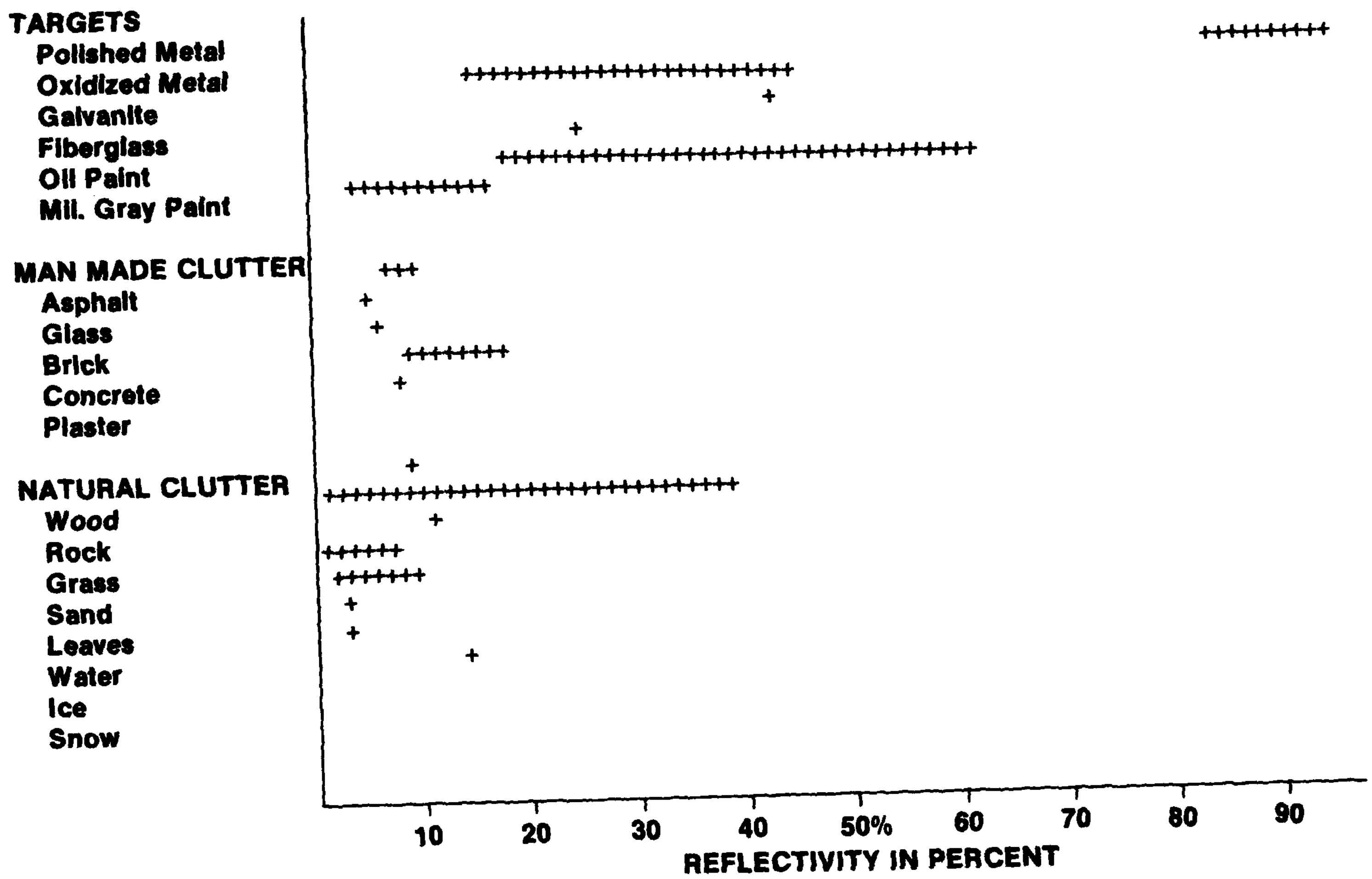

Figure 4. Material reflectivities.

TABLE 11. BLACKBODY RADIANT INTENSITIES 8-12.5 μm.

T (°K)	W (mW/cm^2)
260	5.72
265	6.35
270	7.04
280	8.54
290	10.22
300	12.10
305	13.12
310	14.18
315	15.29
320	16.46
350	24.52
450	64.32
600	153.32

TABLE 12. RADIANT INTENSITIES

CALCULATED FOR 8-12 μm, 300°K AMBIENT				
	W_T (mW/cm^2)	ρ	ϵ	ϵW_T (mW/cm^2)
TARGET				
Body	13.1-14.2	.15-.45	.55-.85	7.21-12.07
Exhaust	42.0-407.2	.15-.45	.55-.85	23.1-346
Effective (350°K)	24.52	.15-.45	.55-.85	13.49-20.84
FLARE	503.3	.01	.99	498
FIRE	232-503	.01	.99	220-498
TREES	13.1-14.2	.03-.1	.90-.97	11.8-13.8
GRASS	13.8-14.7	.12	.88	12.1-12.94
EARTH	14.2-16.5	.02-.08	.92-.98	13.1-16.2
CONCRETE	14.2-16.5	.10-.18	.82-.90	11.6-14.9
ASPHALT	15.3-18.9	.08-.10	.90-.92	13.8-17.4
ROCKS	14.2-16.5	.02-.40	.60-.98	8.52-16.2
WATER	12.0-12.8	.04	.96	11.5-12.3

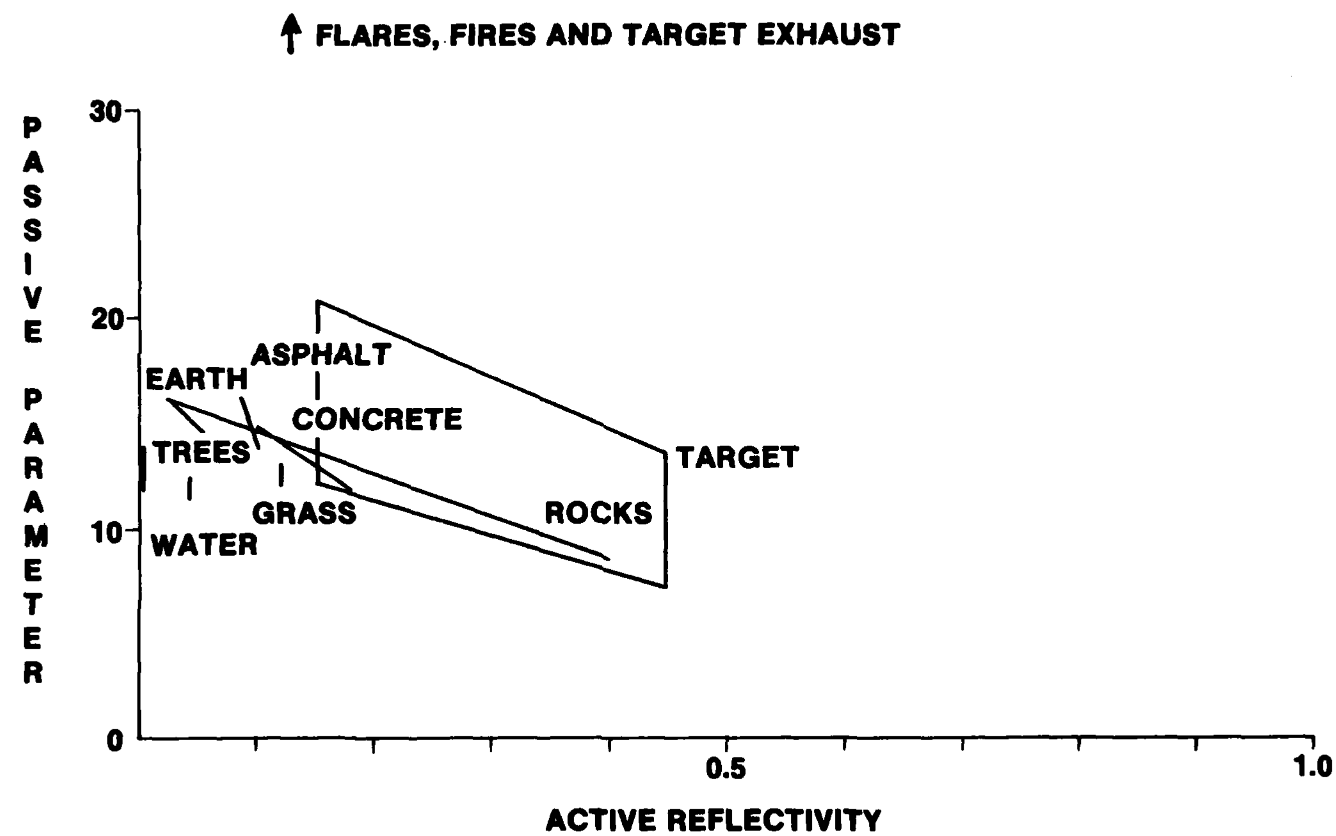

Figure 5. Active/passive diagram.

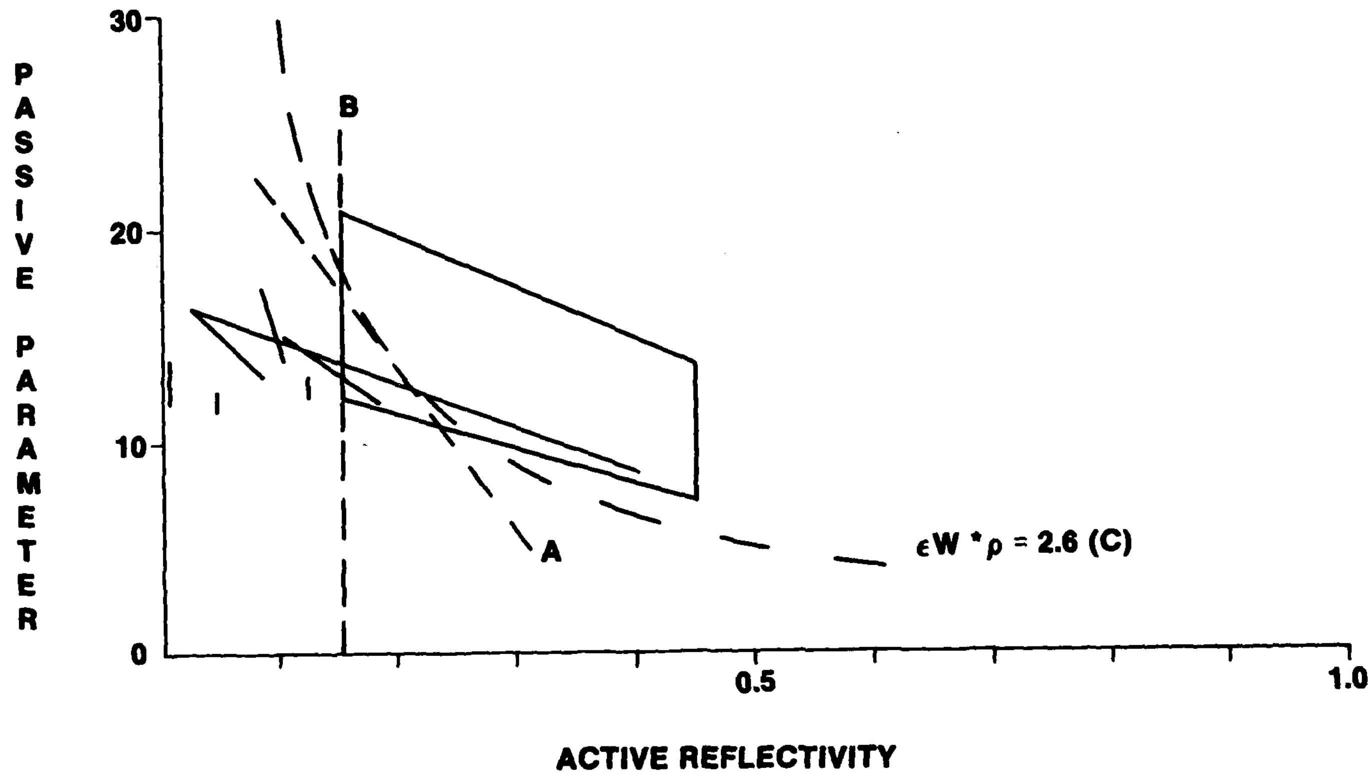

Figure 6. Active/passive dicriminants.

E. Operational Limitations

The previous discussion has been based on the assumption that estimates of the quantities ϵW and ρ are available. There are several possible approaches to determine these quantities which are afforded by the unique combination of active and passive systems. The most important factor is the range information derived from the pulsed active system lidar.

As discussed earlier the irradiance at the seeker in the active system is given by:

$$H_a = \rho P_o \exp(-2\alpha R)/R^2 \qquad [1]$$

with the active system alone, the reflectivity and atmospheric absorption coefficient are unknown quantities. In the passive system,

$$H_p = \varepsilon W(FOV)^2 \exp -\alpha R \qquad [2]$$

and ϵ, W and α are unknown quantities. Using the laws of conservation of energy

$$\rho = 1 - \varepsilon \qquad [3]$$

for objects which are opaque and diffuse Lambertian reflections. Most metallic objects will have both specular and diffuse components. The primary effect of this is that specular reflections will produce apparent "superreflective" objects. This will not be a problem, since these objects are most likely targets.

Equations 1, 2 and 3 contain four unknowns, ρ, τ, W, and α, and therefore cannot be solved directly. Several methods for obtaining some of the unknown quantities may be considered. First of all, the atmospheric attenuation coefficient α can be measured over short path lengths. As an alternative, α may simply be estimated from current atmospheric conditions. In addition, from the range of possible temperatures and ambient measurements, W can be estimated. For backgrounds, the variation in W is around $\pm$ 13 percent in the 8-14 μm region. As another approach, based on only the three equations, discriminants can be derived using relationships between the various quantities such as the product ϵW, the ratio of W/ρ, or the difference between active and passive cumulative statistics. *Figures* 7 through 9 show some of these choices as they would appear on the two-color diagram.

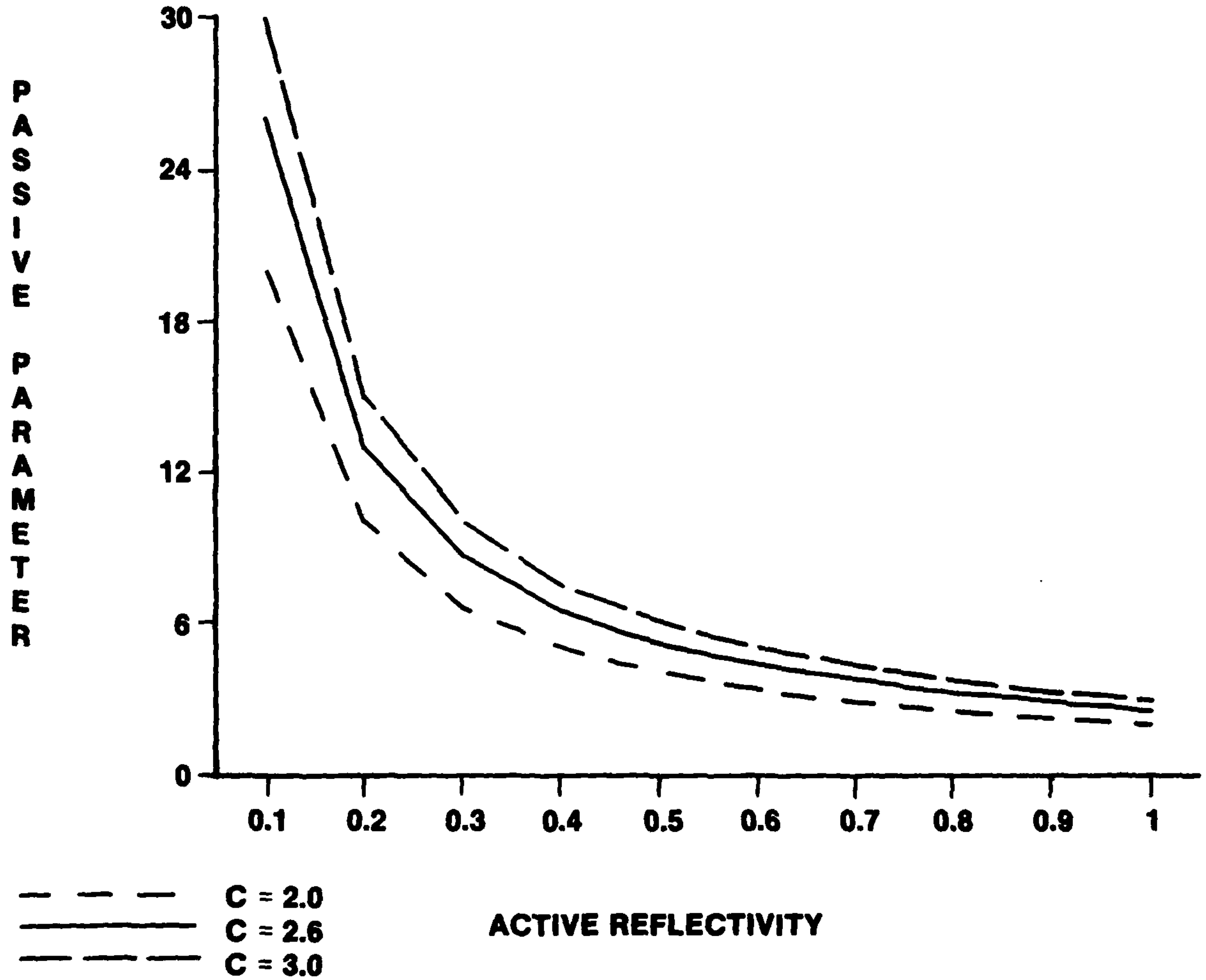

Figure 7. Constant product discriminants.

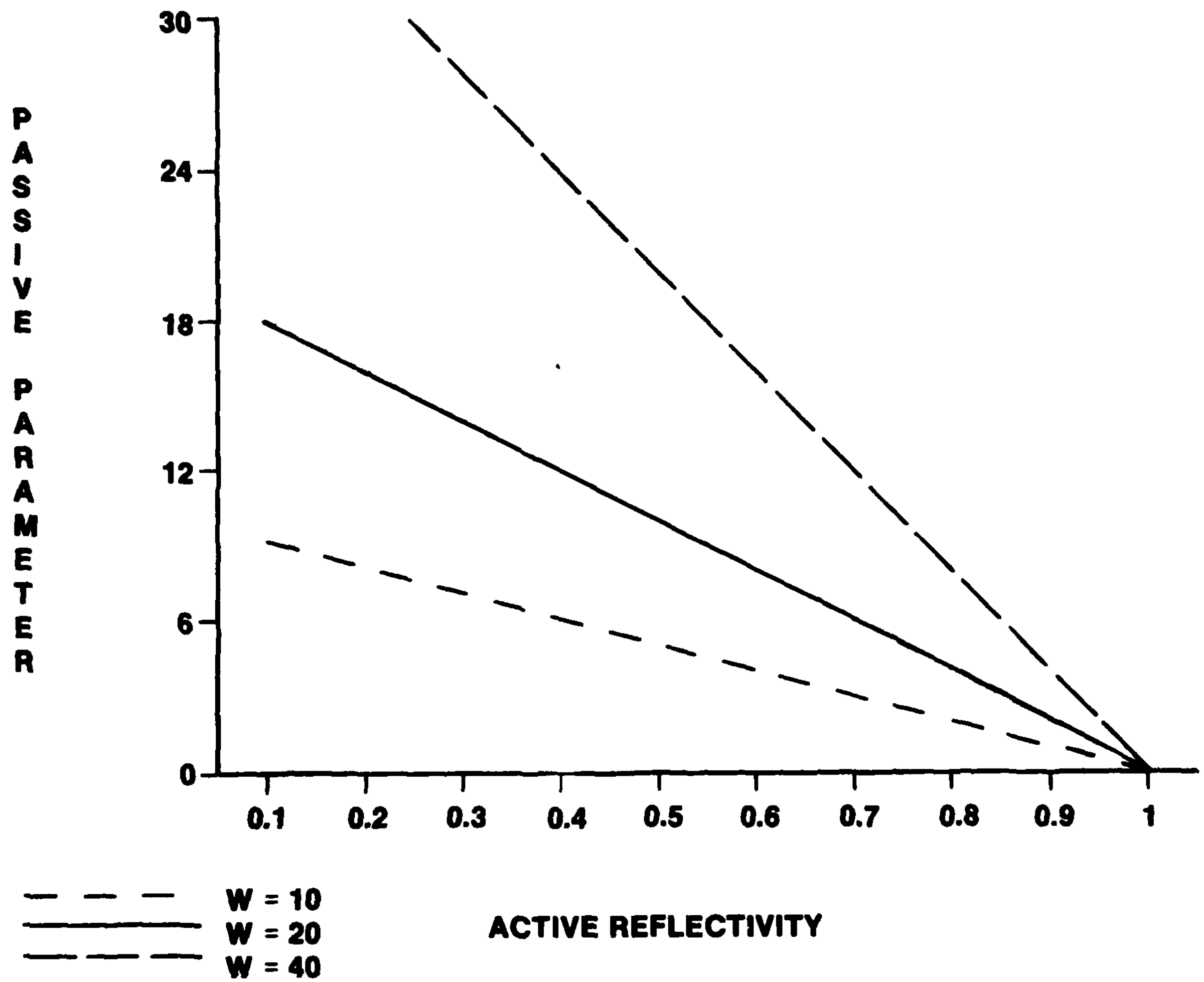

Figure 8. Constant W discriminants.

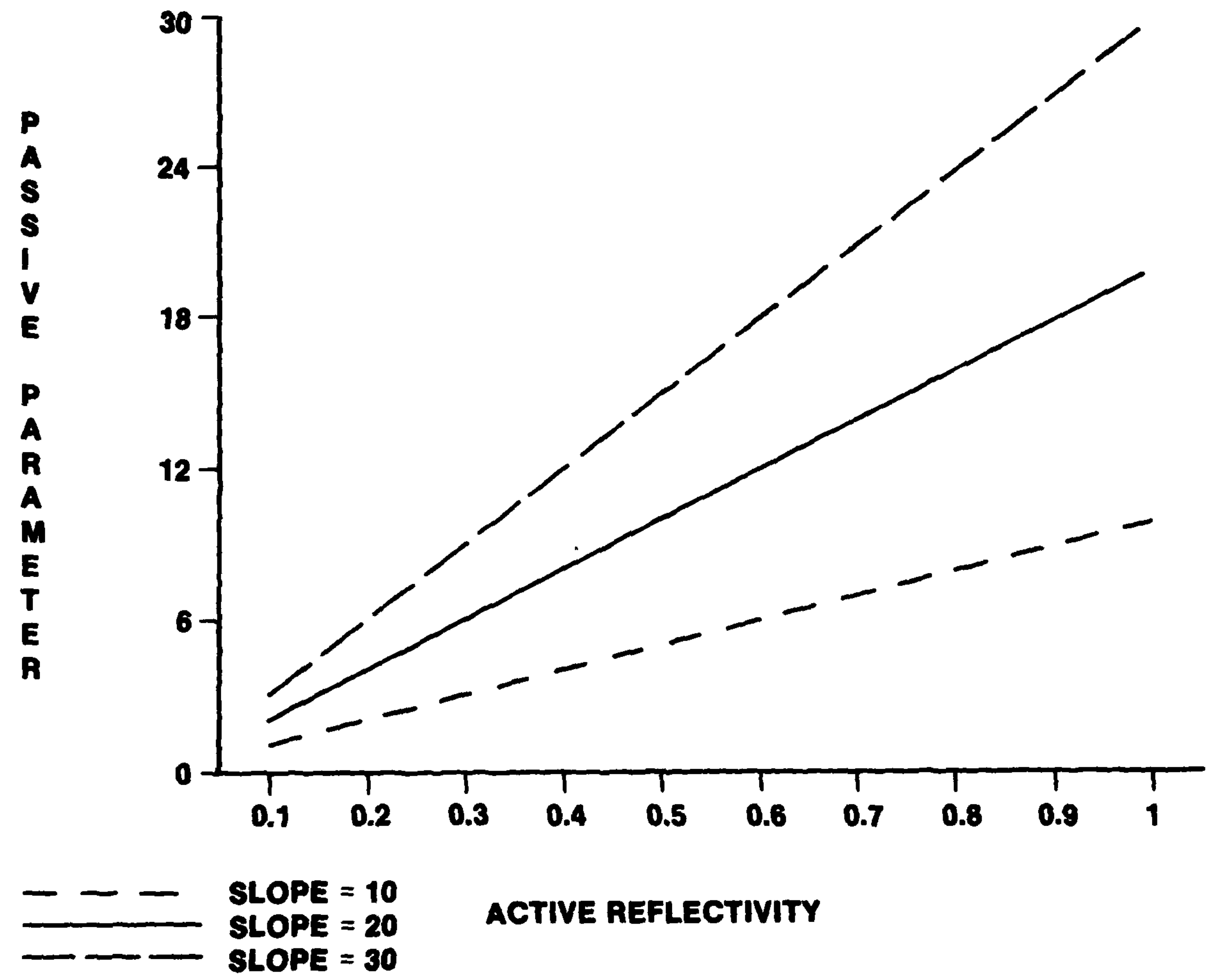

Figure 9. Constant ratio discriminants.

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